HIGH DIMENSIONALITY CARRIERLESS AMPLITUDE PHASE MODULATION TECHNIQUE FOR RADIO OVER FIBER SYSTEM

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DEDICATION

Special for my beloved family especially my father and mother,
Jaafar bin Mohd Nor and **Raedah binti Md Dehan**
And to all friends.

Also to my encouraging supervisor,
Dr. Maisara binti Othman

Thanks a lot for their patient, kindness and cooperation.
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ABSTRACT

Advanced modulation formats such as carrierless amplitude phase (CAP) modulation technique is one of the solutions to increase flexibility and high bit rates to support multi-level and multi-dimensional modulations with the absence of sinusoidal carrier. Recent work are focussing on the 2D CAP-64 QAM Radio-over-Fiber (RoF) system but no extension of higher dimensions is reported. This thesis expands the area of CAP modulation technique and RoF system. The work described in this thesis is devoted to the investigation of 1.25 GSa/s sampling rate for multi-level and multi-dimensional CAP in point-to-point (P2P) and RoF system at 3 km single-mode fiber (SMF). Another advanced modulation format which is known as discrete multitone (DMT) is compared with CAP modulation in order to observe the performance in different modulation schemes. The 4QAM-DMT and 16QAM-DMT at different number of subcarriers are carried out in this propagation. Based on the results, the transmission performance in terms of BER and received optical power for RoF transmission are degraded to almost 3 dB when comparing to 3 km SMF transmission. These are caused by the wireless power loss and impairment effects. The bit rate and spectral efficiency can be increased with the increasing number of levels, and may decreased once the number of dimensions is increased due to the higher up-sampling factor. However, the additional dimensions can be used to support multiple service applications. Therefore, it can be concluded that CAP has better performance as compared to DMT in terms of higher spectral efficiency and data rate. To conclude, the results presented in this thesis exhibit high feasibility of CAP modulation in the increasing number of dimensions and levels. Thus, CAP has the potential to be utilized in multiple service allocations for different number of users.

ABSTRAK

Format modulasi lanjutan seperti teknik modulasi *carrireless amplitude phase* (CAP) adalah salah satu penyelesaian untuk meningkatkan fleksibiliti dan kadar bit untuk menampung modulasi pelbagai-peringkat dan pelbagai-dimensi dengan ketiadaan pembawa sinusoidal. Kajian terkini memberi tumpuan kepada 2D CAP-64QAM sistem *Radio-over-Fiber* (RoF) dan tiada lanjutan untuk dimensi yang lebih tinggi. Tesis ini memperluaskan skop kajian dalam bidang teknik modulasi CAP dan sistem RoF. Kerja-kerja penyelidikan yang dihuraikan di dalam tesis ini adalah dikhaskan untuk menyiasat 1.25 GSa/s kadar pensampelan bagi pelbagai-peringkat dan pelbagai-dimensi teknik modulasi CAP dalam penghantaran optik dan sistem RoF pada 3 km gentian mod tunggal (SMF). Pada masa yang sama, format modulasi lanjutan lain yang dikenali sebagai *discrete multitone* (DMT) telah dibandingkan dengan modulasi CAP untuk melihat prestasi dalam skim modulasi yang berbeza. 4QAM-DMT dan 16QAM-DMT pada nilai subpembawa yang berbeza telah dijalankan dalam penyebaran ini. Berdasarkan dari keputusan yang diperolehi, prestasi penghantaran dari segi BER dan penerimaan kuasa optik untuk penghantaran RoF berkurangan hampir 3 dB berbanding penghantaran 3 km SMF. Ini adalah akibat daripada kehilangan kuasa tanpa wayar dan kesan kemerosotan. Di samping itu, peningkatan jumlah peringkat juga boleh meningkatkan kadar bit dan kecekapan spektrum. Namun, apabila jumlah dimensi meningkat, kadar bit dan kecekapan spektrum akan berkurangan disebabkan oleh faktor kenaikan-pensampelan yang lebih tinggi. Walau bagaimanapun, penambahan dimensi boleh digunakan untuk menyokong pelbagai aplikasi perkhidmatan. Dengan itu, dapat disimpulkan bahawa modulasi CAP mempunyai prestasi yang lebih baik berbanding dengan modulasi DMT dari segi peningkatan kecekapan spektrum dan kadar data. Secara ringkas, hasil keputusan yang dibentangkan di dalam tesis ini menunjukkan kebolehan yang tinggi bagi modulasi CAP dalam peningkatan jumlah dimensi dan peringkat. Oleh

itu, CAP berpotensi untuk digunakan dalam pelbagai perkhidmatan yang diperuntukkan kepada jumlah pengguna yang berbeza.

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LIST OF SYMBOLS AND ABBREVIATIONS

W	-	Bandwidth
f_B	-	Boundary frequency
g_j	-	CAP receiver of FIR filter
f_i	-	CAP transmitter of FIR filter
$z(n)$	-	Composite signals
F_i	-	DFT of vector f_i
s_i	-	Dimensions
f_c	-	Frequency suitable for passband filters
f_1	-	In-phase filter
$f_{B,\min}$	-	Minimum bandwidth
N	-	Modulation dimensionality
k	-	Number of bits per symbol
D	-	Number of dimensions
L	-	Number of levels in each dimension
$x_i(n)$	-	Original sequence of symbols
$F_{i,HP}$	-	Out-of-band portion of transmitter response above f_B
f_2	-	Quadrature filter
h_{RC}	-	RC waveform
α	-	Roll-off factor
$P(f_i)$	-	Shift matrix that operates on vector f_i
h_{SRRC}	-	SRRC waveform
T	-	Symbol period
$s_i(n)$	-	Symbol vector
u	-	Up-sampled signal

$\tilde{0}$	-	Vector of all zeros
$\tilde{\delta}$	-	Vector with one unity element
μm	-	micrometre
1D	-	1-Dimensional
2D	-	2-Dimensional
3D	-	3-Dimensional
3G	-	Third Generation
4D	-	4-Dimensional
A/D	-	Analog-to-Digital
ADC	-	Analog to Digital Converter
ADSL	-	Asymmetric Digital Subscriber Line
AM/PM	-	Amplitude Modulation/Phase Modulation
ASICs	-	Application-Specific Integrated Circuits
ASK	-	Amplitude Shift Keying
ATM	-	Asynchronous Transfer Mode
B2B	-	Back-to-back
BBoF	-	Baseband-over-Fiber
BER	-	Bit Error Rate
Bit/s/Hz	-	Bit per second per Hertz
BS	-	Base Station
CAP	-	Carrierless amplitude phase
CATV	-	Community Access Television
CCI	-	Cross-channel Interference
CD	-	Chromatic Dispersion
CPFSK	-	Continuous-Phase Frequency Shift Keying
CS	-	Central Station
CW	-	Continuous Wave
D/A	-	Digital-to-Analog
D8PSK	-	Differential 8-ary Phase-Shift Keying
DAC	-	Digital to Analog Converter
DAS	-	Distributed Antenna System
dB	-	decibel
dBm	-	millidecibel

DBPSK	-	Differential Binary Phase-Shift Keying
DFE	-	Decision Feedback Equalization
DFT	-	Discrete Fourier Transform
DMLs	-	Directly Modulated Lasers
DMT	-	Discrete Multitone
DM-VCSELs-based	-	Directly Modulated VCSELs-based
DQPSK	-	Differential Quadrature Phase-Shift Keying
DR	-	Dynamic Range
DSL	-	Digital Subscriber Line
DSP	-	Digital Signaling Processing
E/O	-	Electrical-to-Optical
EMLs	-	External Modulated Lasers
EVM	-	Error Vector Magnitude
FDC	-	Fiber Distribution Cabinet
FDP	-	Fiber Distribution Point
FEC	-	Forward Error Correction
FFT	-	Fast Fourier Transform
FIR	-	Finite Impulse Response
FPGA	-	Field-Programmable Gate Array
FPI	-	Fabry-Perot Interferometer
FTB	-	Fiber Termination Box
FTTH	-	Fiber-to-the-Home
FWS	-	Fiber Wall Socket
Gbps	-	Gigabit per second
GHz	-	GigaHertz
GPRS	-	General Packet Radio Service
GSa/s	-	Gigasample per second
GSM	-	Global System for Mobile
HAN	-	Home Access Network
HD	-	High-Definition
HDTV	-	High Definition Television
I	-	In-phase
ICI	-	Inter-carrier Interference
IFFT	-	Inverse Fast Fourier Transform

IFoF	-	Intermediate Frequency-over-Fiber
IM-DD	-	Intensity Modulation-Direct Detection
IQ	-	Inphase-Quadrature
ISI	-	Inter-symbol Interference
ISM	-	Industrial, Scientific, and Material
km	-	kilometer
L/D	-	Level per Dimension
LANs	-	Local Area Networks
LO	-	Local Oscillator
M^2-CAP	-	Multi-level Carrierless Amplitude Phase
mA	-	milliAmpere
Mbaud	-	Megabaud
Mbps	-	Megabit per second
MCMC	-	Malaysian Communications and Multimedia Commission
MMF	-	Multi-mode fiber
mm-wave	-	milimetre-wave
M-PAM	-	Multi-level Pulse Amplitude Modulation
MSK	-	Minimum Shift Keying
MZI	-	Mech-Zehnder Interferometer
MZM	-	Mech-Zehnder Modulator
NF	-	Noise Figure
NGA	-	Next Generation Access
nm	-	nanometre
NRZ	-	Non-Return Zero
NRZ-OOK	-	Non-Return Zero On-Off Keying
O/E	-	Optical-to-Electrical
OA	-	Optimization Algorithm
ODMA	-	Orthogonal Division Multiple Access
OFDM	-	Orthogonal Frequency Division Multiplexing
OFM	-	Optical Frequency Multiplying
ONU	-	Optical Network Unit
OOFDM	-	Optical Orthogonal Frequency Division Multiplexing
OOK	-	On-Off Keying

OQPSK	-	Offset Quadrature Phase Shift Keying
P2P	-	Point-to-Point
PAM	-	Pulse Amplitude Modulation
PAPR	-	Peak-to-Average Power Ratio
PD	-	Photodetector
PIN PD	-	Positive-Intrinsic-Negative Photodetector
PMD	-	Polarization Mode Dispersion
PMMA	-	Polymetyl Methacrylate
POF	-	Polymer Optical Fiber
PON	-	Passive Optical Network
PR	-	Perfect Reconstruction
PRBS	-	Pseudo random binary sequence
PSK	-	Phase Shift Keying
Q	-	Quadrature
QAM	-	Quadrature Amplitude Modulation
QPSK	-	Quadrature Phase Shift Keying
RAP	-	Radio Access Point
RAU	-	Remote Antenna Unit
RC	-	Raised Cosine
RC-LED	-	Resonance Cavity Light Emitting Diode
RF	-	Radio Frequency
RFoF	-	Radio Frequency-over-Fiber
RGB-LED-based	-	Red, Green, Blue-Light Emitting Diode-based
RHD	-	Remote Heterodyne Detection
RoF	-	Radio-over-Fiber
ROP	-	Received Optical Power
RRC	-	Root-Raised Cosine
RZ	-	Return Zero
SE	-	Spectral Efficiency
SFDR	-	Spurious Free Dynamic Range
SI-POF	-	Step-Index Plastic Optical Fiber
SMF	-	Single-mode fiber
SM-VCSEL	-	Single-mode VCSEL
SNR	-	Signal-to-Noise Ratio

SRRC	-	Square-root Raised Cosine
SSB	-	Single-Sideband
SSMF	-	Standard single-mode fiber
TDM	-	Time Division Multiplexing
VCSELs	-	Vertical Cavity Surface Emitting Lasers
VDSL	-	Very-high-bite-rate Digital Subscriber Line
VLC	-	Visible Light Communication
VOA	-	Variable Optical Attenuator
VoD	-	video-on-Demand
VoIP	-	Voice-over-IP
WDM	-	Wavelength Division Multiplexing
Wi-Fi	-	Wireless Fidelity
WLANs	-	Wirelss Local Area Networks
xQAM	-	x-Quadrature Amplitude Modulation

LIST OF PUBLICATIONS

Journals:

(i) M. B. Jaafar, M. B. Othman, N. M. Ridzuan, M. F. L. Abdullah, "1.25 Gbps and 2.5 Gbps Data Rate Transmission of 2D-CAP Modulation for Access Network", *ARPN Journal of Engineering and Applied Science*, 11(8), 5066-5070. April 2016. *(published)*

(ii) N. M. Ridzuan, M. B. Jaafar, M. B. Othman, M. F. L. Abdullah, "Optical Transmission System Employing Carrierless Amplitude Phase (CAP) Modulation Format", *ARPN Journal of Engineering and Applied Science,* 11(14), 8776-8780. July 2016. *(published)*

(iii) M. B. Jaafar, M. B. Othman, N. M. Ridzuan, M. F. L. Abdullah, "Simulation of High Dimensionality Carrierless Amplitude Phase (CAP) Modulation Technique of RoF system", IET Optoelectronic. *(On-going)*

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(i) M. B. Jaafar, M. B. Othman, N. M. Ridzuan, M. F. L. Abdullah, R. Mohamad, T. Kanesan, "Simulation of High Dimensionality Carrierless Amplitude Phase (CAP) Modulation Technique", *6th International Conference on Photonics (ICP)*. 14-16 March 2016. Kuching, Sarawak. *(published)*

(ii) N. M. Ridzuan, M. B. Othman, M. B. Jaafar, M. F. L. Abdullah, "Comparison of CAP and QAM-DMT Modulation Format for In-home Network Environment", IDECON 2016. 19-20 October 2016. Langkawi. *(presented)*

LIST OF AWARD

(i) **Bronze Medal in Research & Innovation (R&I) Festival UTHM (2-3 November 2014):**
M. B. Jaafar, M. B. Othman, N. M. Ridzuan, M. F. L. Abdullah. "2D-CAP Modulation for In-home Network."

(ii) **Bronze Medal in Malaysia Technology Expo (MTE) 2015 (12-14 February 2015):**
M. B. Othman, I. Tafur Monroy, J. B. Jensen, M. B. Jaafar, N. M. Ridzuan, M. F. L. Abdullah. "High Dimensionality CAP Modulation Technique for Access Network."

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter discusses the background of advanced modulation scheme for optical communication system and optical carrierless amplitude phase (CAP) modulation format. A scenario of home area network (HAN) and an overview of Radio-over-Fiber (RoF) system architecture are briefly described to define the significance of CAP modulation format. The problem statement is also discussed along with the objectives and scope of work.

1.2 Background of Study

The development of new technologies in telecommunication systems has increased the demand of new devices that require better network planning and design. This is due to fact that conventional communication network infrastructures such as twisted-pair telephony and coaxial cable CATV networks are not suitable enough in the growth of recent network traffic demand, as shown in Figure 1.1 (Cisco, 2016). From the figure, mobile data traffic is expected to grow to 30.6 exabytes per month by 2020.

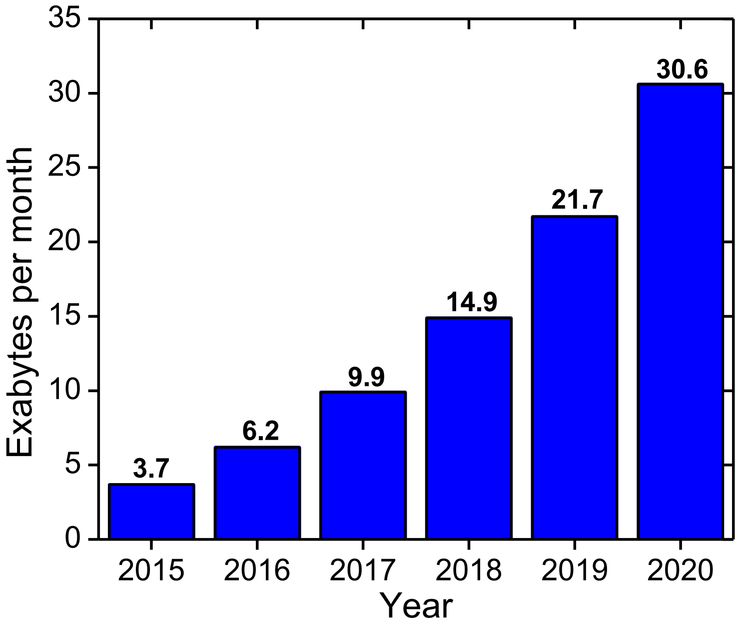

Figure 1.1: Global mobile data traffic (Cisco, 2016).

In high-speed communication networks, the digital subscriber line (DSL) techniques, namely asymmetric digital subscriber line (ADSL), very-high-bit-rate digital subscriber line (VDSL), and cable modem are employed. However, the cost of these systems is too high. Therefore, wireless technology and fiber optics have revolutionized these local telecommunications network, so that high-speed communication networks can be developed at an affordable cost.

1.2.1 Introduction to Advanced Modulation Format for Optical Communication System

Optical fiber communication systems are widely utilized mainly for two reasons. Firstly is the requirement to obtain lower cost and secondly, is the wider bandwidth due to the increase of data exchange (Winzer & Essiambre, 2006). Recently, multiple wavelength channels have received special attention in optical fiber communication system to obtain higher data exchange. However, the system are costly and can be reduced by using a minimum number of wavelengths. Hence, different modulation formats are utilized in future optical networks that rely on the system features, bit rate, and network size (Mishina et al., 2006).

Consequently, on-off keying (OOK) in both of non-return to zero (NRZ) and return-to-zero (RZ) are becoming the main modulation formats for most of the optical communication systems (Gnauck & Winzer, 2005). The NRZ-OOK is deployed in long-haul high-speed 10 Gigabit per second (Gbps) transmission networks (Borne, 2008). However, these modulation formats present low spectral efficiency for future high speed networks.

Recently, higher order modulation formats are broadly studied for long haul optical communication systems. These high order modulation formats include quadrature phase shift keying (QPSK), quadrature amplitude modulation (QAM), and orthogonal frequency division multiplexing (OFDM) with coherent detection and digital signaling processing (DSP) algorithm (Tao et al., 2013). For external modulation, IQ modulator is normally utilized at the transmitter, and optical hybrid and local oscillators together with DSP algorithms at the receiver. These sources are implemented by using application-specific integrated circuits (ASICs) for signal detection.

However, coherent detection technique is unrealistic to be used for short reach communication link. In addition, the use of IQ modulator and optical hybrid does not only increase the system cost, but also increases the complexity of system integration. The short reach optical communication system requires a low-cost light sources. For example, directly modulated lasers (DMLs), vertical cavity surface emitting lasers (VCSELs), and external modulated lasers (EMLs). These sources directly detect the signal at the optical receiver. Therefore, no optical phase information will be accessible.

As a result, further research need to be done to increase the system spectral efficiency when using DML, EML, VCSEL or direct detection. Moreover, the atention over advanced modulation schemes that include pulse amplitude modulation (PAM) (Wei, Geng, et al., 2012 & Ghiasi et. al., 2012), carrierless amplitude phase (CAP) modulation (Othman M. B., 2012 & Lopez, 2013), direct detected OFDM and discrete multitone (DMT) modulation (Othman M. B. et al., 2014 & Gui T., 2013) are also necessary.

1.2.2 Introduction to Carrierless Amplitude Phase Modulation Format

CAP modulation technique is a multilevel and multidimensional modulation scheme that shows certain similarities to QAM in terms of its capability to transmit two data

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